

Positive and negative sequence currents to improve voltages during unbalanced faults

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1 Introduction

Grid faults constitute a group of unfortunate events that cause severe perturbations in the grid. The voltages can take values below the established minimum, or on the contrary, exceed the maximum in non-faulted phases. The currents are also susceptible to vary considerably. Traditional power systems based on synchronous generators could encounter currents surpassing the nominal values, and therefore, the fault could be clearly detected. However, the increasing integration of renewables [3] supposes a change of paradigm, in which currents can be controlled but are limited so as not to damage the Isolated-Gate Bipolar Transistors (IGBT) found in the Voltage Source Converter (VSC) [1].

Transmission System Operators (TSO) are responsible for imposing requirements related to the operation under voltage sags to generators and converters [10, 8]. Such requirements are gathered in the respective grid codes. There seems to be no clear consensus on how to restore the voltage. In this sense, even if for instance the Low Voltage Ride Through (LVRT) profiles present similarities [6], analysis aimed at determining analytically the optimal injection of positive and negative sequence currents are not numerous. As far as we are aware, only Camacho et al. offer an optimal solution regarding the injection of active and reactive powers [5].

Consequently, this work focuses on finding the most convenient positive and negative sequence currents (and not powers) to raise the voltage at the point of common coupling. First, a simple model is discussed, and then, the results are shown together with the corresponding discussion. Despite the elegance found in closed-form expressions, we obtain the optimal operating point by either computational brute force or an iterative process with the help of the SciPy library. The expressions regarding the several types of fault studied as well as its correspondent diagrams are shown in the appendix.

2 Definition of the system

The system we are considering is formed by an ideal grid (only positive sequence voltage is present) coupled to a VSC. The model is depicted in Figure 1. The VSC will be controlled in a way that leads to an improvement in the voltage at the PCC.

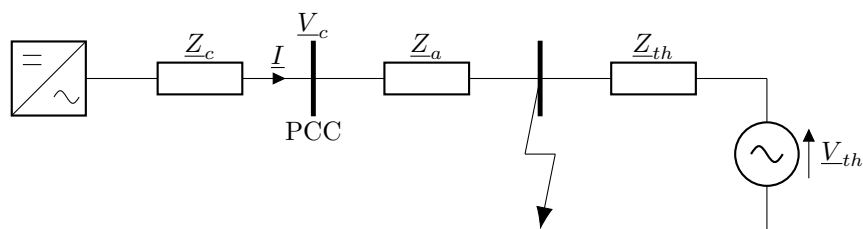


Figure 1: Single-phase representation of the simple system under a fault

This study considers the balanced fault type but also the unbalanced ones, which include the line to ground, the double line to ground and the line to line fault. The model in Figure 1 attempts to describe simple yet sufficient system to test the influence of the injected currents by the VSC on the

voltage at the PCC. The system could be complicated by adding parallel capacitances on both sides of \underline{Z}_a to model a hypothetical submarine cable. However, we prioritize keeping the system simple.

We are concerned with improving the voltage \underline{V}_c as a function of the current \underline{I} injected by the converter. Formally speaking there is no clear definition on what improving the voltage means as it depends on rather pre-established preferences. For instance, one could try to maximize the positive sequence voltage, minimize the negative sequence voltage or even maximize the difference between both. These three strategies have been covered in [5]. A more flexible approach is based on defining the objective function as

$$f(\underline{I}^+, \underline{I}^-) = \lambda^+ (|\underline{V}_c^+(\underline{I}^+, \underline{I}^-)| - 1) + \lambda^- (|\underline{V}_c^-(\underline{I}^+, \underline{I}^-) - 0|), \quad (1)$$

where the weighting factors $\lambda^+, \lambda^- \in \mathbb{R}$. By adjusting these factors one can follow the three aforementioned strategies. Note that the goal is to obtain a positive sequence voltage as close as possible to one (in per unit) while simultaneously approaching zero in the negative sequence voltage. Even though the problem is described as a function of the positive and negative sequence currents, it could also be stated as a function of the original *abc* currents without loss of generality. The associated expressions are gathered in the appendix as well.

Minimizing f does not come with complete freedom. That is, the currents are constrained so as not to exceed the IGBT limits. It becomes more convenient to express the constraints in the *abc* frame:

$$g(\underline{I}_a, \underline{I}_b, \underline{I}_c) = \begin{cases} |\underline{I}_a| \leq I_{max}, \\ |\underline{I}_b| \leq I_{max}, \\ |\underline{I}_c| \leq I_{max}. \end{cases} \quad (2)$$

For now we are not concerned with the voltages imposed to the semiconductors due to the fact that the filter \underline{Z}_c is most likely to take small values. In practical situations current limitations are the most serious constraint. Therefore, we define the optimization problem as follows:

$$\min_{\underline{I}^+, \underline{I}^-} f(\underline{I}^+, \underline{I}^-) \quad (3a)$$

$$\text{subject to } g(\underline{I}_a, \underline{I}_b, \underline{I}_c), \quad (3b)$$

where the currents in the *abc* frame can be related to the currents expressed in the symmetrical components form by means of Fortescue's transformation, and viceversa [7]. As a direct consequence of that, the analysis can be performed in the *abc* frame while expressing the voltages as a function of the positive, negative and homopolar components. Another valid procedure is to work with the symmetrical components and relate the currents to the *abc* ones. Both ways to confront the problem are equally valid. The results obtained in this study have been generated and validated with both paths.

Current grid codes define the low voltage ride through (LVRT) limit curve which indicates the relation between the duration of a fault and the voltage frontier that indicates if, for instance, a wind turbine ought to disconnect. Such LVRT curves present slight variations from country to country [10] but they all share the same pattern: in case of a severe fault, the disconnection should not take place if it has a low duration; on the contrary, less noticeable faults imply a larger connection time. Grid codes usually impose a curtailment of active power enforce the generation of reactive power in order to collaborate on raising the voltage [2, 9].

Nevertheless, studies dealing with determining the optimal currents to inject are not precisely numerous. At most, [4] express the voltages in terms of active and reactive power but do not consider constraints. [5] formulate the optimization problem and arrive to a closed-form expression, even though it becomes iterative. The analysis is performed contemplating powers rather than currents. Because of that, this work focuses on computing the optimal currents to increase the positive sequence voltage as close to one as possible and achieving a negative sequence voltage that approaches zero. In essence, the results that follow come from solving Equations 3a and 3b.

3 Analysis

Four types of fault are considered in this study. One is the balanced fault, which yields a simple yet valuable system to analyze the distribution of optimal currents. The remaining faults are unbalanced: the line to ground, the line to line and the double line to ground cases.

4 Conclusion

This study has covered the analysis of a simple system to determine the optimal currents that ought to be injected to raise the positive sequence voltage and decrease the negative sequence voltage in case of a fault. Four types of faults have been considered. Despite the particularities, since the system is mainly inductive, the optimal active currents tend to be close to zero, while the optimal reactive currents become substantial. As a direct consequence, we conclude by saying that injecting only reactive powers, as imposed by the grid codes, is likely to be a near-optimal strategy for systems where lines are highly inductive.

In addition to that, this work proposes two methodologies to arrive to the optimal solution. One consists of computing combinations where currents can take a wide range of values. When the intervals are small enough, such computationally intensive approach matches with the solution coming from solving directly the optimization problem. The results indicate that the double line to ground fault is the hardest in terms of minimizing the objective function. Besides, we have shown the presence of multiple optimal points for the line to ground fault.

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